Research and Development Technical Report

ECOM-6036

ANALYSIS OF WIND DATA FROM A SOUTH CAROLINA COASTAL FOREST

By
Joseph H. Shinn

February 1969

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UNITED STATES ARMY ELECTRONICS COMMAND
ATMOSPHERIC SCIENCES LABORATORY, RESEARCH DIVISION
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TR ECOM-6036
February 1969

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OSD-1366

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FROM A SOUTH CAROLINA COASTAL FOREST

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DA Task No. 1B0-62109-A197-02

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U. S. Army Electronics Command

Atmospheric Sciences Laboratory

Fort Huachuca, Arizona

ABSTRACT

This report summarizes the mean wind and turbulence characteristics in and above a jungle-like South Carolina coastal forest. The data reported are from one trial of several conducted in a field study by Melpar, Inc. Very little interpretation of the data is given.

The vegetation was black gum - red maple. Data on leaf area density estimates as well as stem densities are tabulated. The mean vector wind had two notable features: a nearly constant speed in the lowest two-thirds of the canopy, and a turning of the wind direction with height in the same layer. All three components of turbulence intensity were larger below the canopy, especially the longitudinal component. Variance spectra of the vector wind speed indicated that an inertial subrange existed at all heights above and below the canopy, and that as far as could be determined the energy dissipation rate was nearly constant with height.

The diffusion of fluorescent particles from a point source at ground level showed that the initial drift was in a direction 60° to the left of the wind direction above the canopy, but beyond a distance of 100 m from the source the centerline of the plume gradually turned to the right. The lateral cross-sections of plume concentration were skewed to the left.

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ANALYSIS OF WIND DATA FROM A SOUTH CAROLINA COASTAL FOREST

The purpose of this report is to summarize the mean wind and turbulence characteristics in and above a jungle-like South Carolina coastal forest. The data reported are from a field study conducted by Melpar, Inc., in the summer of 1964.[1] We have performed most of the wind data analyses ourselves directly from raw data which are not available in published form. It is intended that this report should provide selected recent observations which are not available elsewhere, but which are important to the advancement of the state of the art of turbulent diffusion studies.

We will select one particular trial (#11 of 13 trials) during which the equipment was most reliable and the speeds the highest. Wind speed, elevation, and azimuth sensors (MRI "vectorvanes") were used at eight height intervals up to 60 meters. The forest canopy was just over 30 meters high. The vectorvanes below the tree crowns were operative although not very active. The system tolerances for the sensors were (1) speed: ± 20 cm sec^{-1}, (2) azimuth: $\pm 8°$, (3) elevation: $\pm 3°$. The data were sampled at a rate of 5.56 scans per second. The trial period was 135 minutes, beginning at 2130 hours EST, 12 August 1964. The site was under strong pre-frontal winds from a cold front 240 km to the north. Upper air observation were made by pilot balloon and theodolite. The main tower site was 300 meters from a forest road and 3 km from any forest border.

Within the system tolerances for temperature the temperature profile, in the layer up to 57 meters, was for all purposes isothermal at $25.75°C \pm 0.05°C$ and thus slightly stable.

1. DESCRIPTION OF VEGETATION

The vegetation within a 150 meter radius of the main tower site was relatively homogeneous in composition and stature. Beyond 150 meters there was to the west an area characterized as "low swamp", and to the east an area characterized as "pine ridge". These areas were different in composition and stature from the tower area. It can be assumed, however, that flow transition was not seriously affected by this difference since the tree tops tended to

1. A summary of this study has been presented by Allison, Herrington, and Morton (1).

merge uniformly in the horizontal. The tower area was characterized as "high swamp". Detailed measurements of the forest physiognomy and composition were made in the high and intermediate swamp areas. We will combine these data for purposes of characterizing the forest within a 100 meter radius of the tower site. The major species are black gum and red maple. Other species are tupelo gum, bald cypress, loblolly pine, possum oak, sweet gum, and holly. These "other" trees are mostly small understory trees. The densities (stems per acre) near the tower area were as follows, indicating the difference between the high and the intermediate swamps.

	High Swamp	Intermediate Swamp
Black Gum	106	145
Red Maple	40	130
Other	72	33
Total	218	309

The relationship between diameter at breast height (dbh) and tree height was not significantly different for the high and intermediate swamp areas. On the basis of this similarity in stature we will combine the two areas to describe the tower area.

Using the following assumptions and statistical correlations, it is possible to compute a vertical distribution of L(z), leaf density (surface area per unit volume.) From detailed physiognomic measurements of randomly selected red maple and black gum trees, it was found that regardless of tree size or species the mean leaf area density in surface area (one side) per unit tree crown volume for all measured crowns was 0.41 m^{-1} with an error of 0.07 m^{-1}. Since this is a relatively small error considering all the possible factors of biological variability we shall assume that this density in each crown was a constant, and that the effects of tree size and species are irrelevant in determining how leaves occupy the available space within a crown. To convert this density to a land area basis for the forest, we multiply the value of 0.41 m^{-1} by A, the average crown cross sectional area at a given height level, and by N, the number of trees per unit ground area in that height class.

That is:

$$L(z)=0.41N(z)A(z)\ m^{-1}$$

The density of trees (stems per acre)was measured for different height classes and we use this for $N(z)$. We will have to make use of some statistical correlations to obtain $A(z)$.

The average cross sectional area $A(z)$ can be estimated by dividing the crown volumes D of a given height class by the average thickness of the crowns. D was not measured on a height class basis. The non-linear correlation between crown volumes D (m^3) and tree diameters, dbh (inches), was as follows:

$$D=4.5(dbh)^{1.655}$$

This correlation was fitted to the combined data and a standard error in D of 197% was obtained. Although the relative error is large, D ranged over nearly two orders of magnitude. Considering the problems in sampling and measuring crown volumes we shall assume that all the errors were sampling errors, and that the above correlation is the best possible estimate.

Let us now show that the dbh size classes can be converted to height size classes with the aid of nonlinear statistical correlation formula between dbh (inches) and tree height H(feet) as follows:

$$H=13.1(dbh)^{0.7}$$

This correlation was fitted to the combined high and intermediate swamp data for a standard error in H of 29%.

By applying the above assumptions and correlations to the tree measurements we were able to obtain a distribution of leaf area density $L(z)$ as well as the height integrated index $L_I(z)$ defined as follows:

$$L_I(z) = \int_0^z L dz \qquad \text{(dimensionless)}$$

It should be noted that the value of L_I obtained at the top of the forest is equivalent to the "leaf area index" (LAI) used in agricultural work. LAI is defined as the total leaf area of the crop divided by the land area occupied by the crop. The estimated leaf area summary is given in Table 1, and is shown graphically in the right sides of Figures 1, 3, and 4.

The leaf area density distribution for the coastal

Table 1. Leaf area distribution, South Carolina black gum - red maple coastal forest

Height m	Leaf Area Density, $L(z)$ (m^2/m^3)	Height Integrated Index, L_I (dimensionless)
3.55	0.016	0.028
6.60	0.047	0.126
9.65	0.068	0.303
12.20	0.026	0.470
15.15	0.036	0.561
16.35	0.035	0.603
19.40	0.066	0.763
22.45	0.114	1.034
25.50	0.160	1.451
28.55	0.045	1.762
31.60	0.008	1.844
32.00	0.000	1.846

Table 2. Tree densities versus diameter size classes, South Carolina black gum - red maple coastal forest.

diameter at breast height (dbh), size class (inches)	tree densities (stems per acre)
3	73.4
4	35.7
5	18.3
6	19.5
8	22.5
10	14.6
12	19.6
14	16.8
16	16.8
18	16.5
20	10.1

forest had two local maxima, one near 10 meters, presumably an understory, and one near 25 meters, the superior crown density. The LAI for the forest was 1.85 or approximately one-half what one would expect for a dense corn crop. It should be mentioned that stem area densities were determined to be 5.5% of the leaf area densities.

Other data which are useful in describing the vegetation are the summarized tree densities (stems per acre) versus dbh (inches). These data show that in the tower area the trees are "all-aged" with nearly uniform densities between the size classes of 5 to 18 inches dbh. The absence of significant variations in the densities in this size range indicates that the forest has been undisturbed during its history. See Table 2.

2. MEAN VECTOR WIND

A long-term average was computed for the vectorvane data. Over the 135-minute sampling period these computations usually included a total of more than 45000 data points for each height level. The azimuth angles were averaged using a special process to effectively remove the discontinuity between 360° and 0°. The elevation angles averaged to zero within the system tolerances except for the vectorvane at the next lowest height (9.2m) which averaged to -13.4° for an average vertical speed of -2.3 cm/sec. This is likely to be an instrument malfunction, however.

It should be noted that the vectorvane at 28.7m was on a different tower and in a strict sense its data should be excluded from the analyses. The average azimuth angles at 59 m and at 3.8 m could possibly be erroneous. We believe the azimuth angles are erroneous at 59 m and 3.8 m but admit to a preconceived notion of what should occur. The mean azimuth angle at 59 m is smaller than values below it and above it in a layer where this should not occur. This could be due to improper referencing. On the other hand the mean azimuth angle at 3.8 m could have been biased by the inertia of the instrument and periods of inactivity more than instruments above. The FP cloud drift is a better indicator of low level wind drift than the instrument at 3.8 m. According to Morton (2), project manager, the speed measurement at 9.2 m is "suspect" due to malfunction.

The speed and direction of the mean vector wind at different height levels are given in Table 3-A. Supplemental wind speed and direction data are given in Table 3-B, which are upper air theodolite (pilot balloon) observations, a Bendix "Aerovane" at 58 m (insensitive to

Table 3A. Speed and direction of the mean vector wind. 135 minute average, "vectorvanes".

Height (m)	Speed (cm sec^{-1})$\pm$20.0	Azimuth (^{o})$\pm$8.0
59.0	447	228.2*
44.1	396	247.1
37.8	339	251.6
32.4	259	241.6
28.7	135**	267.3**
18.8	29	234.7
9.2	11*	215.3
3.8	29	250.2*

Table 3B. Supplemental wind observations.

Height (m)	Type	Speed (cm sec^{-1})	Azimuth (^{o})
1500.***	Theodolite	2560	----
610.	Theodolite	1850	265.0
58.	Aerovane	521	239.0
1.5	FP cloud	24	215.0

* Assumed erroneous.

** Not on the same tower as other data.

*** Estimated.

turbulence), and fluorescent particle (FP) cloud trace at 1.5 m. Figure 1 shows graphically that the speed of the mean vector wind dropped off rapidly through the tree crowns and was nearly constant with height beneath the crowns. Also included on Figure 1 is the leaf density distribution L(z) which displays the principal drag-producing characteristic of the forest. Figure 2 depicts a turning of the wind 30° to the right from ground level up to the tree tops, which is verified by the FP trace but we have ignored the 3.8 m azimuth measurement. This phenomenon of turning of the wind has been verified in other similar studies not reported here (1).

Some other parameters of importance which we report here are related to the mean vector wind above the tree crowns. By least-squares fitting of the logarithmic velocity profile to the speed values above the tree tops we obtained the following micrometeorological parameters and their standard errors:

1. zero plane displacement, 2908 $\pm$80 cm

2. roughness length, z_o, 16.81 $\pm$8.90 cm

3. friction velocity, U_*, 34.67$\pm$3.58 cm/sec

The fitted values of speed for the log profile were as follows:

HEIGHT (m)	CALCULATED SPEED (cm/sec)
59.0	449.1
44.1	389.3
37.8	342.2
32.4	258.4

3. TURBULENCE CHARACTERISTICS

The high rate of sampling enabled computation in three dimensions of the intensity of turbulence and the coefficients of anisotropy. Let us define a turbulent velocity fluctuation which has a longitudinal component u' in the direction of the mean vector wind, a lateral component v' that lies in the horizontal plane with a direction perpendicular to the mean vector wind, and a vertical component w'. The standard deviation, S, of each velocity component is defined as follows:

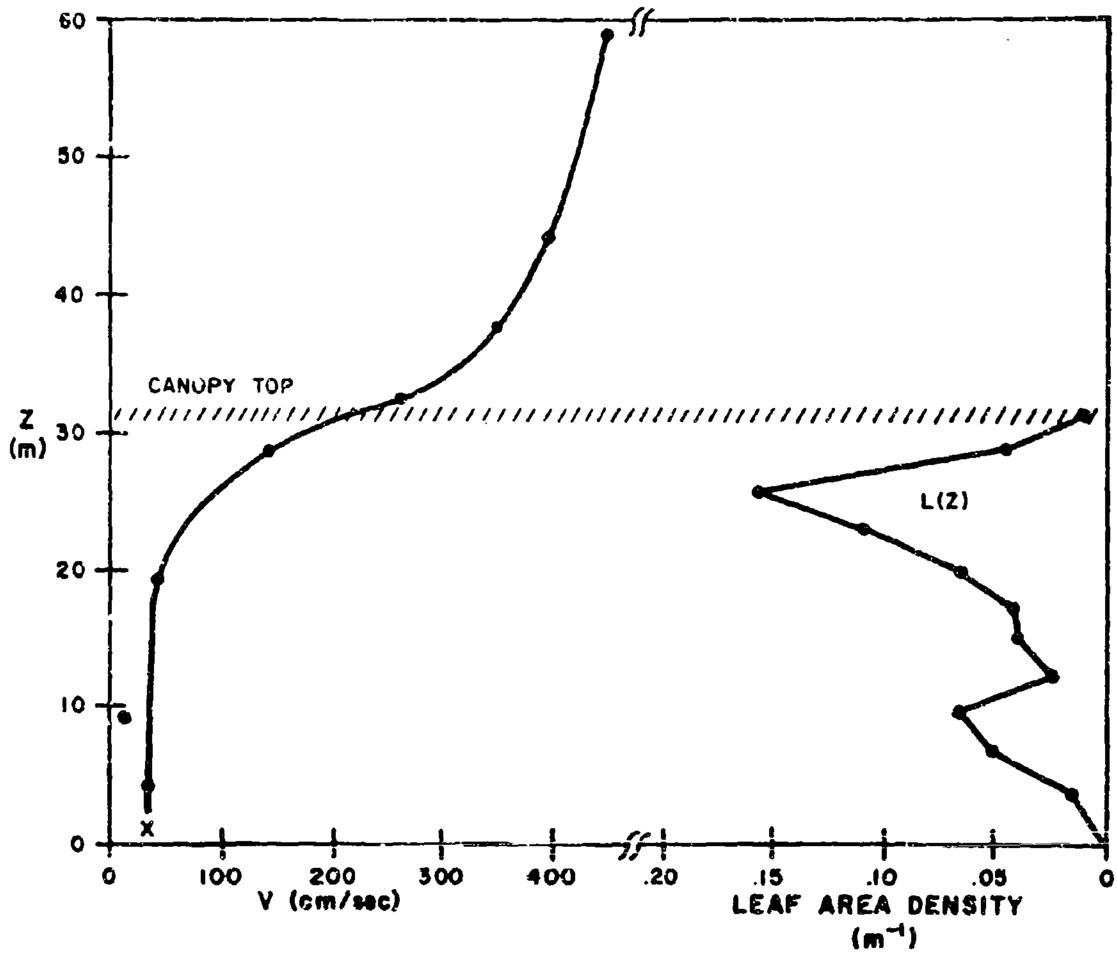

Figure 1. The speed of the mean vector wind V measured by vectorvanes and by FP cloud drift (x). Shown also is the leaf area density L.

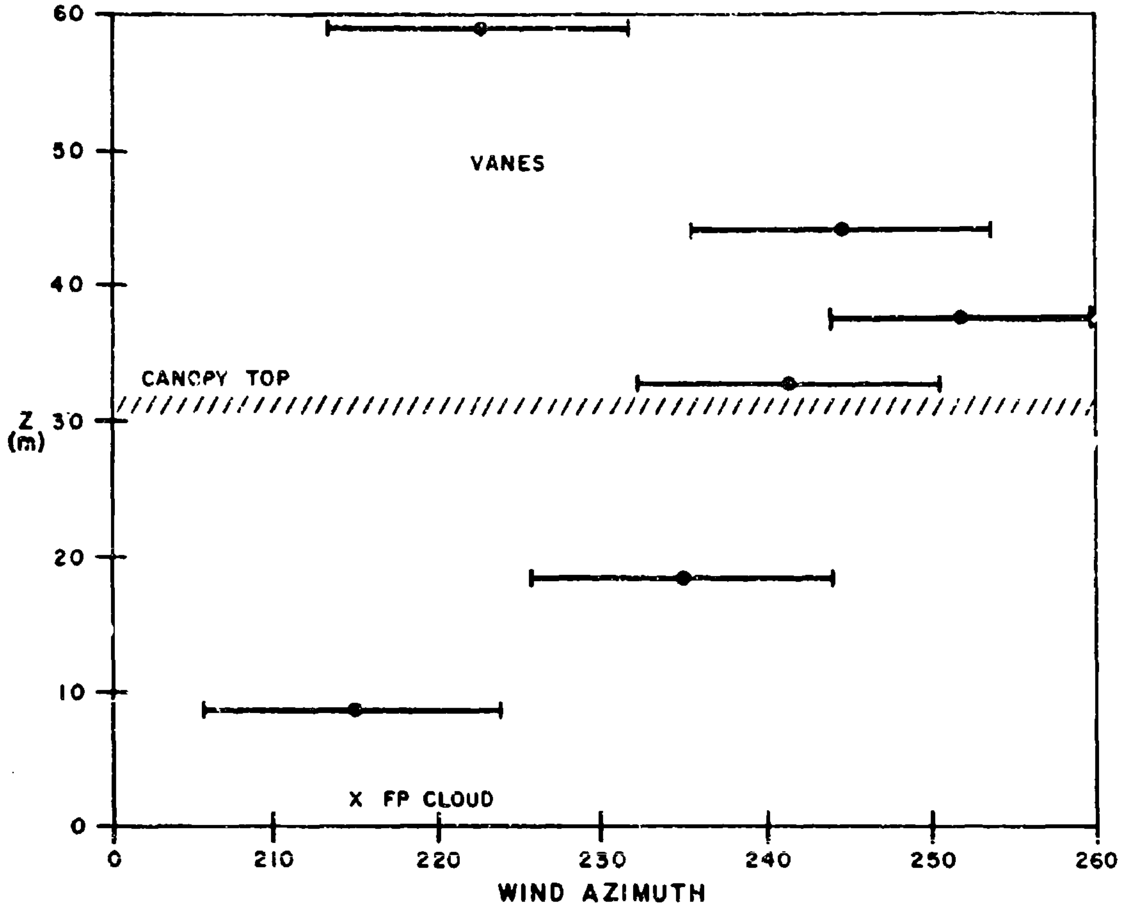

Figure 2. The horizontal direction of the mean vector wind showing turning with height under the canopy. FP cloud drift is indicated by (x).

$$S_u = \sqrt{\overline{u'^2}}\ , \qquad S_v = \sqrt{\overline{v'^2}}\ , \qquad S_w = \sqrt{\overline{w'^2}}$$

where the bar denotes a long-term averaging process. The fluctuations are instantaneous variations from the long-term components of the mean vector wind.

The intensity of turbulence, I, in each component direction is defined as follows:

$$I_u = S_u/V, \qquad I_v = S_v/V, \qquad I_w = S_w/V$$

where V is the speed of the mean vector wind.

The coefficients of anisotropy indicate the degree of fluctuation in any component direction relative to the fluctuation in the longitudinal direction. In the lateral direction the coefficient of anisotropy is S_v/S_u, and in the vertical, S_w/S_u. These express the relative shape of the turbulent eddies.

We found that there was a slight temporal trend in the wind direction azimuth during the 135-minute averaging time. For that reason S_v was computed by averaging 27 five-minute values of S_v. This technique, however, filters out all variations of periodicity greater than five minutes at the same time it eliminates trends. Alternative methods of removing the trends were tried but rejected on the basis of the degree of subjectivity in a curve-fitting process. No trends were removed in either the S_u or S_w computation.

The longitudinal component of turbulence intensity attained a value greater than 1.0 at the lowest height levels of the forest. This means the fluctuations were usually greater than the mean speed. A secondary maximum occurred just above tree-top height undoubtedly due to the local influence of tree spires on the flow, see Figure 3.

The lateral component of turbulence intensity also had a maximum in the region of the crowns. The vertical component of turbulence intensity was distributed parallel to the lateral component, except the values were one-half as large as those of the lateral component. All the data of turbulence intensity are presented in Table 4 and are shown graphically in Figure 3.

The coefficients of anisotropy (Figure 4) show that above the tree crowns the eddy dimensions are about the

Table 4. Turbulence intensity components.

height (m)	S_u/V	S_v/V	S_w/V
59.0	0.281	0.330	0.163
44.1	0.305	0.335	0.174
37.8	0.364	0.347	0.182
32.4	0.699	0.387	0.287
18.8	0.895	0.445	0.327
9.2	1.222	0.329	0.191
3.8	0.767	0.329	0.064

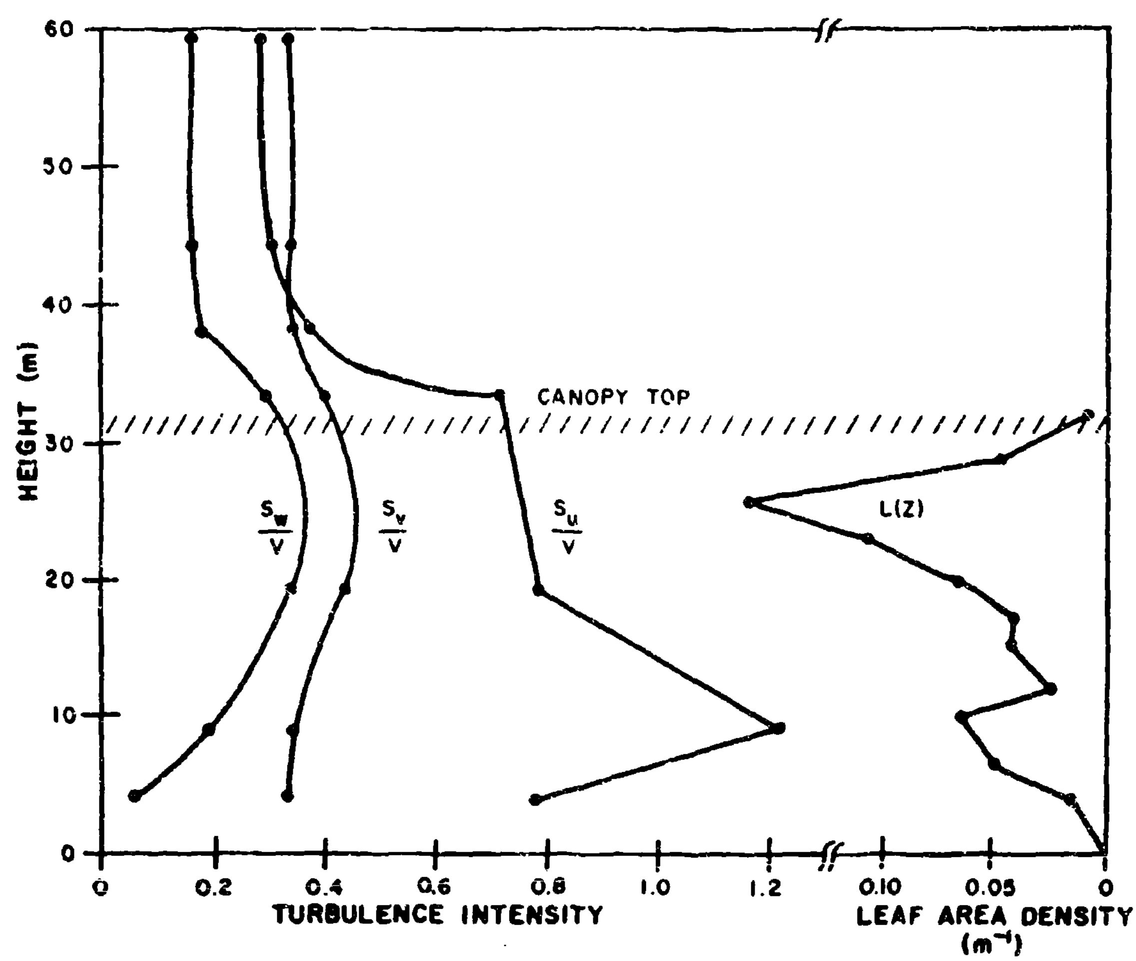

Figure 3. Profile of the three u,v,w components of turbulence intensity. Shown also is leaf area density L.

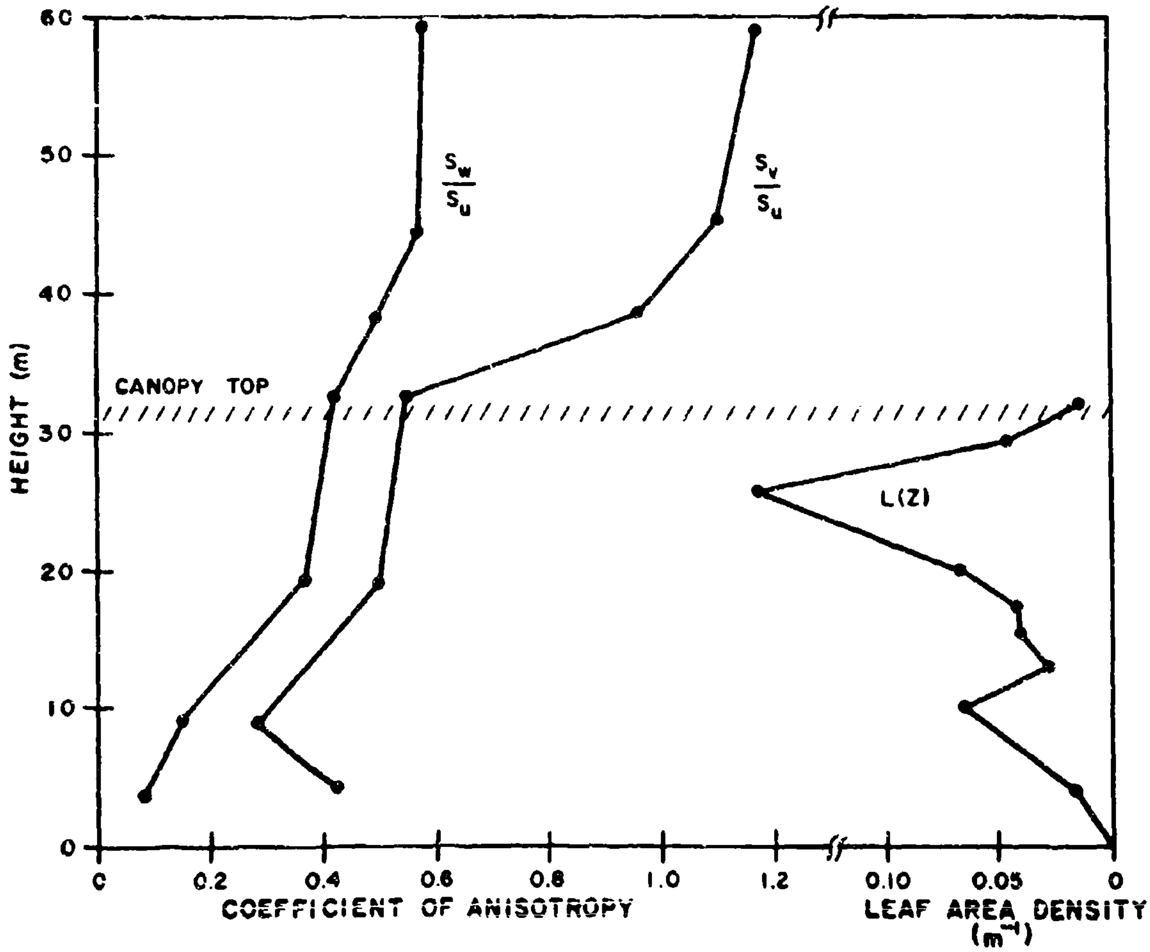

Figure 4. Profiles of the coefficients of anisotropy. Also shown is leaf area density L.

same (isotropic) for both components in the horizontal plane x,y. But the vertical component shows 2:1 compression in the vertical plane (disc-shaped). On the other hand, the eddy shape below the tree crowns has a dominant longitudinal axis but is compressed about 2:1 in the lateral and vertical axes (cigar-shaped). These data are not listed since they can be computed from the data of Table 4.

It should be emphasized that these components are computed in a locally natural co-ordinate system. That is, x is in the direction of the long-term average wind, which is not the same at each height, and y is normal to x in the horizontal plane. Thus the turbulence intensities do not reflect variances due to systematic turning of the wind with height.

Because of the high sampling rate, the turbulence data lend themselves to spectral evaluation of the variance of the wind speed components. Data analysis for the variance spectra of the vector wind speed follows.

4. VARIANCE SPECTRA OF THE VECTOR WIND SPEED.

A procedure developed by Maynard, McBride, and Stoner (3) was used to determine the variance spectrum of the speed of the vector wind (which is practically equal to the speed of the horizontal wind). This procedure defines the variance spectrum as the Fourier transform of a given time series into a frequency domain. Following Bendat and Piersol (4), the variance spectrum was written as the real part of a finite, discrete Fourier transform, and a "Hanning window" was used as a smoothing function to the spectral estimates.

The number f spectral estimates is determined by the number of lags chosen to compute the autocorrelation function. If the number of lags is large the reliability of each estimate is low while the detail of the spectral density function is greater, and vice versa. We chose 120 lags as an appropriate number to obtain sufficient detail and reliability. The raw data were averaged in non-overlapping groups of 5 before spectral processing (equivalent to a 0.90 sec sample in real time). This reduced the number of data points to 9000.

The number of points in a running mean was determined by trial and error. In the first series 24, 121, and 201 points were tried and it was found that 24 points gave unbelievable, unstable results while 121 and 201 points gave identical results at high frequencies. At low frequencies, however, 201 points caused an apparent loss of

information. In the second series the number of points in the running mean was varied systematically at 81, 101, 121, 141, 161, and 181 points, and tests of variance were made as follows. At the low frequency end of the data range, it was found that a -5/3 power law was approached assymptotically in the spectral density estimate for all height levels. It was assumed that an inertial sub-range was extant at the low frequency end of the data range. Thus the spectral density function was expected to be that indicated by Lumley and Panofsky (6)

$$E_k = 0.138\, e^{2/3}\, k^{-5/3}$$

Where e is the energy dissipation rate and k is wave number (cycles per unit length). We tested the effect of the number of points in the running mean by finding which value gave the minimum variance of e in the low frequency (low k) end of the data range.

Values of the computed energy dissipation rate e, were found to be surprisingly conservative with height through the forest canopy and the boundary layer above. The computed e values and their error estimated by the minimizing process described above are presented in Table 5. The values of e do not drop off rapidly with height in the boundary layer as do Ball's values in Lumley and Panofsky (6). However, they are of the same order of magnitude as Ball indicates for heights of 10 to 100 m.

The fact that e is practically constant with height through the forest canopy means that wherever the -5/3 law holds, the spectral estimates E_k at different height levels will be practically indistinguishable. This is evident in the plots of E_k versus k where considerable overlap occurs between heights, see Figure 5.[2] It should be emphasized that these data were taken during almost perfectly isothermal conditions so that the potential temperature gradient was positive at 0.01 deg m^{-1} (slightly stable).

At higher wave numbers (higher frequencies) the spectral estimates deviate sharply from the -5/3 power, especially at low levels within the forest canopy. These

2. For convenience of plotting, spectral estimates at wave numbers greater than 3×10^{-4} cycles cm^{-1} were averaged in non-overlapping groups of five.

Table 5. Turbulent energy dissipation rate, e, and its standard error, S_e, for wave numbers less than the upper limit of the inertial subrange. Below the canopy (32m) the limiting wave number was 1.5×10^{-3} cycles cm^{-1}.

Height	e	S_e
m	$cm^2\ sec^{-3}$	$cm^2\ sec^{-3}$
59.0	158	34.8
44.1	120	19.6
37.8	133	44.4
32.4	214	83.0
18.8	106	41.2
9.2	149	67.0
3.8	54	15.4
Average	134	49.1

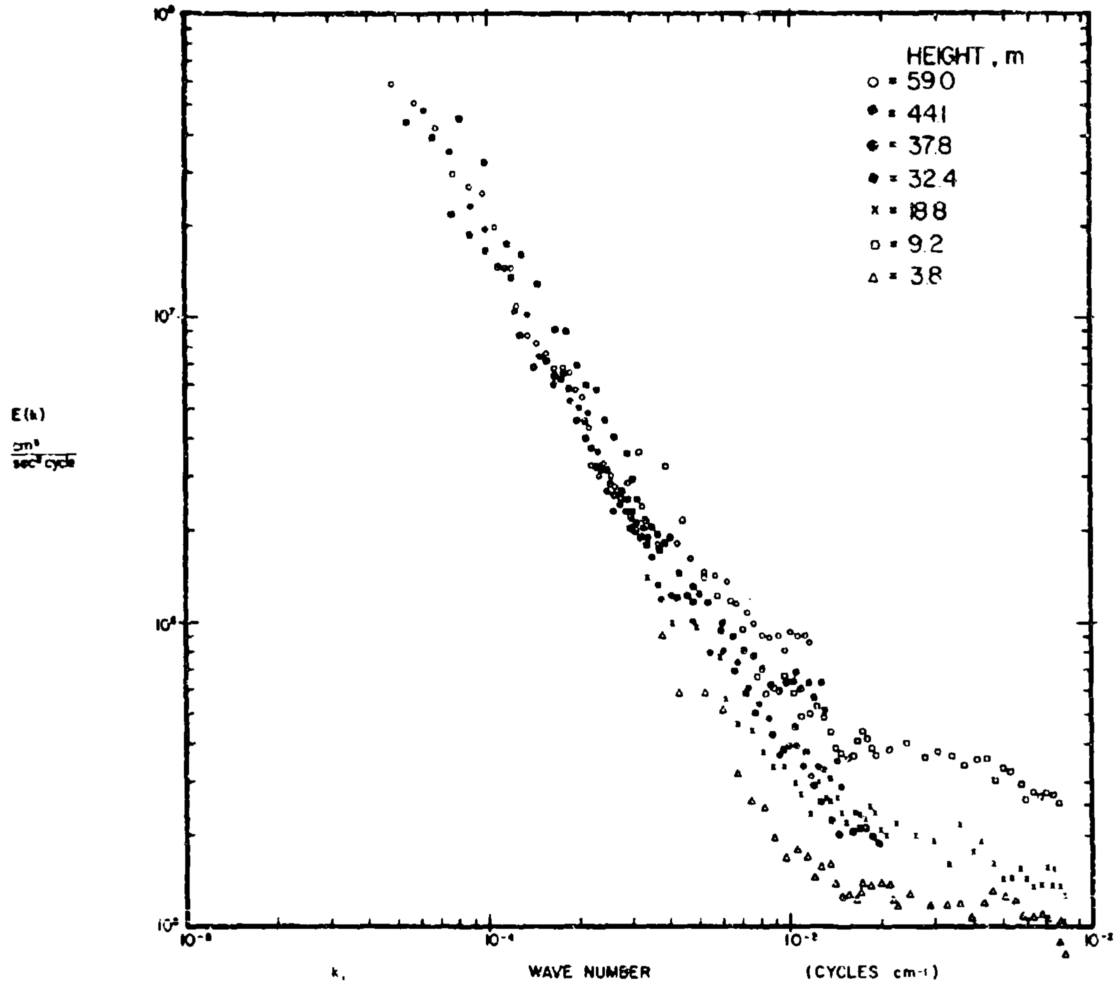

Figure 5. Observed spectral energy density of the wind speed at heights above and below the canopy.

deviations occur over a significant range of wave numbers that they cannot be assumed to be an artifact of data analysis. In fact aliasing of the data is not suspected because of the high data acquisition rate (5.56 scans per sec) and because the original data were averaged in non-overlapped groups (0.90 sec) comparable to the time lag of the vectorvane speed sensor.

The deviation from a -5/3 power to a different slope indicates the limit of the inertial subrange. At the lower height levels this change is due to momentum extraction by the drag of the irregularly distributed roughness elements (leaves, etc.). The critical wave number where this change occurred was about 1.5×10^{-3} cycles cm^{-1} for the 18.8, 9.2, and 3.8 m height levels, all below the canopy. The new slope of the energy density E_k for wave numbers greater than 1.5×10^{-3} cycles cm^{-1} indicates that a -3/10 power of k defined the distribution, see Figure 5.

5. DIFFUSION CHARACTERISTICS

Fluorescent particles (FP) were released from a bomblet and the fallout was measured downstream on a 100 m horizontal grid network. Different colored FP were used simultaneously. The FP collectors were silicone greased rods called "rotorods".

A brief summary of the diffusion of one of the FP traces released at the height of 1.5 m will be presented. The mean size of the FP was 3.31 microns with a size distribution described as 86% between 0.75 microns and 5.5 microns. The source strength was 10^{11} particles. The settling rate was 0.1 cm sec^{-1}. The total count of FP at the 1.5 height was determined at the trial conclusion. The centerline of the FP plume drifted in a direction about 60° to the left of the wind direction above the tree crowns for a distance of about 100 m from the source. At distances greater than 100 m the plume centerline gradually turned to the right so that at 700 m from the source the direction was about 33° to the left of the wind direction above the trees. In other words the plume had a parabolic trajectory in the horizontal x,y plane.

The distribution of FP was non-symmetric about the centerline. Concentrations were skewed to the left. The maximum total count (rotorods) relative to the source strength decreased along the centerline distance, x; the ratio of maximum counts to the source strength was nearly proportional to $1/x^{2.5}$. The distribution of counts in the y-direction perpendicular to the centerline is

shown schematically in Figure 6 for four chosen distances from the source. The skewness to the left of the plume centerline is evident.

6. SUMMARY

Very little interpretation of the data is given here. It was felt that the presentation of the data is the most important issue at the present time in order that investigators may become cognizant of the basic wind observations made at this particular site. It is hoped that most of the basic questions of observation have been covered.

The vegetation was described as a black gum - red maple coastal forest. The leaf area density distribution was estimated from measurements of physiognomic features of the vegetation. We indicated that the forest was undisturbed during its history as evident in the even distribution of older trees.

The mean vector wind had two notable features in this forest. The mean speed was nearly constant up to heights about two-thirds the height of the canopy. Secondly, the mean wind direction turned with height about 30° to the right in the same layer.

The turbulence intensity changed markedly from above to below the forest canopy. All three intensity components were larger below the canopy and the longitudinal component was especially amplified.

Variance spectra indicated that an inertial sub-range existed at all height levels in the forest for wave numbers less than 1.5×10^{-3} cycles cm^{-1}. There was no significant difference in the inertial sub-range energy dissipation rate above or below the canopy within the errors of estimation of the values. At the lowest heights in the forest the variance spectra had a -3/10 power dependency on wave number for wave numbers greater than 1.5×10^{-3} cycles cm^{-1}.

The diffusion of fluorescent particles in the forest showed that initial drift of a source at ground level was in a direction 60° to the left of the wind direction above the canopy. Beyond a distance of 100 m from the source the centerline of the plume gradually turned to the right and approached the wind direction above the canopy. The maximum concentration dropped off nearly proportional to $1/x^{2.5}$ and the lateral distributions were skewed to the left of the centerline due to turning of the plume.

More analyses will be performed with this data. A series of papers are in preparation interpreting some of

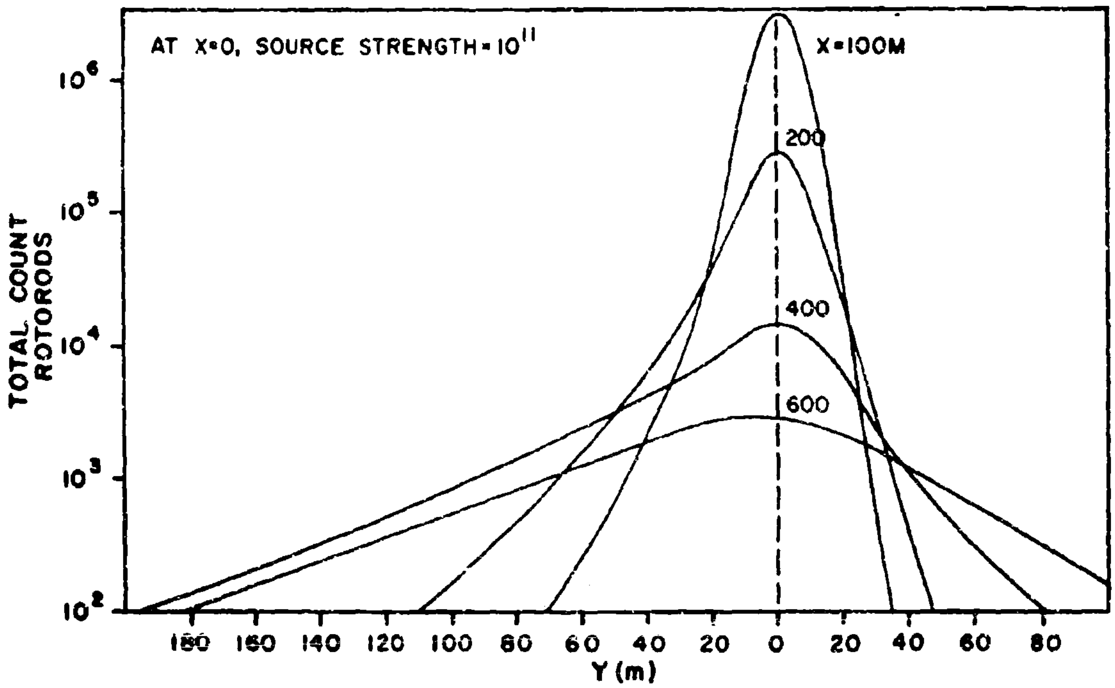

Figure 6. Cross-sections of FP concentrations along the plume centerline at the same height as the release height, 1.5m, and for different distances from the source.

the observations in the light of existing theory and in comparison with the results of other workers.

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UNCLASSIFIED
Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author) U. S. Army Electronics Command Atmospheric Sciences Laboratory Fort Huachuca, Arizona 85613	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP

3. REPORT TITLE

ANALYSIS OF WIND DATA FROM A SOUTH CAROLINA COASTAL FOREST

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)

Joseph H. Shinn

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
February 1969	24	6

8a. CONTRACT OR GRANT NO. b. PROJECT NO. c. DA Task No. 1B0-62109-A197-02 d.	9a. ORIGINATOR'S REPORT NUMBER(S) ECOM-6036 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	U. S. Army Electronics Command Atmospheric Sciences Laboratory Fort Huachuca, Arizona 85613

13. ABSTRACT

This report summarizes the mean wind and turbulence characteristics in and above a jungle-like South Carolina coastal forest. The data reported are from one trial of several in a field study conducted by Melpar, Inc. Very little interpretation of the data is given.

The vegetation was black gum-red maple. Data on leaf area density estimates as well as stem densities are tabulated. The mean vector wind had two notable features: a nearly constant speed in the lowest two-thirds of the canopy, and a turning of wind direction with height in the same layer. All three components of the turbulence intensity were larger below the canopy, especially the longitudinal component. Variance spectra of the vector wind speed indicated that an inertial subrange existed at all heights above and below the canopy, and that as far as could be determined the energy dissipation rate was nearly constant with height.

The diffusion of fluorescent particles from a point source at ground level showed that the initial drift was in a direction 60° to the left of the wind direction above the canopy, but beyond a distance of 100m from the source the centerline of the plume gradually turned to the right. The lateral cross-sections of plume concentration were skewed to the left.

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14. KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Coastal forest (So. Carolina)						
Mean vector wind						
Turbulence intensity						
Leaf area density						
Stem density						
Canopy						
Variance spectra						
Diffusion of fluorscent particles						

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